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Cleanliness improvements of NIF (National Ignition Facility) amplifiers as compared to previous large-scale lasers

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Optical Engineering

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Abstract: Prior to the recent commissioning of the first NIF (National Ignition Facility) beamline, full-scale laser-amplifier-glass cleanliness experiments were performed. Aerosol measurements and obscuration data acquired using a modified flatbed scanner compare favorably to historical large-scale lasers and indicate that NIF is the cleanest large-scale laser built to date.

1. Introduction

The NIF is a flashlamp-pumped multi-aperture laser composed of 192 individual beams[1,2]. The amplifier section for each of these beams consists of 18 Brewster-angle Nd:glass slabs (11 slabs in the main amplifier, 7 slabs in the power amplifier) with a clear aperture of ~40 cm x 40 cm. The amplifier will operate with mean laser fluences up to 25 J/cm^2 at a wavelength of 1053nm (1ω). The interaction of these high laser fluences with contamination on laser glass can lead to damage and/or increased obscurations. Obscurations can be glass damage, glass defects or contamination on the glass surface. In general, laser-glass obscurations lead to increased scatter, thereby decreasing the energy that can be delivered to the target. Large-sized laser-glass obscurations threaten the laser glass directly as well as other downstream optics via holographic imaging process described previously[3,4]. To automate the assessment of the size and distribution of obscurations on laser glass, a customized flatbed scanner assembly was designed and built to acquire obscuration data on laser glass. Actual laser glass damage can be measured by first cleaning the laser glass prior to scanning. During Nova[5,6] decommissioning, we found that the obscuration density on the amplifier glass was nominally independent of both the number of laser shots (180 shots to 8000 shots)[7] and the laser fluence. Data from Amplab[8,9] (a special amplifier test facility built prior to NIF) showed increasing obscurations as a function of flashlamp shots (up to 100 shots) with no laser beam present. The conclusion we draw from these results is that laser glass damage is primarily due to flashlamp light and the majority of this damage occurs early in the amplifier lifetime. The flashlamps are, in essence, blackbody radiators at 10,000 Kelvin and can easily vaporize any number of contaminants. The flashlamp fluence for all of these large-scale lasers is ~10 J/cm^2. Offline experiments have shown that a perfectly clean laser-glass slab in a perfectly clean amplifier environment is not damaged in the presence of flashlamp light[10]. The obscuration density on a laser glass surface has been assumed to represent the overall cleanliness of the amplifier, i.e., more obscurations imply a dirtier environment. In this paper we present and compare historical cleanliness and obscuration data to recent cleanliness and obscuration results from a recent experiment performed on the first commissioned beamline of NIF. These results indicate that NIF is the cleanest large-scale laser built to date.

2. Cleanliness measurement methods and cleanliness effects on large-scale lasers

Cleanliness can be measured in a number of ways and NIF has adopted Fed Std 209[11] for airborne cleanliness and Mil Std 1246[12] for surface cleanliness. Airborne cleanliness is measured using commercial particle counters. For non-optical surfaces, NIF measures surface cleanliness using the PCVS (Particle Cleanliness Validation System)[13]. For laser slabs, NIF measures surface cleanliness using a modified flatbed scanner described in this paper. The NIF has a performance specification of <10% contrast on the 1ω beam. The beam contrast, *Contrast*[14], is given by

$$Contrast \approx \sqrt{2 f_s} \qquad (1)$$

where f_s = scattered fraction = (obscured area) / (beam area).

The NIF specification for each surface of the laser-glass contribution to the total scattered fraction is $2.5\text{x}10^{-4}$. In addition, to psrevent downstream damage due to holographic imaging, the laser-glass amplifiers have an additional requirement on largest obscuration size. For 200-μrad spatial-filter pinholes, this number can be as small as 0.5 mm.

Contamination can impact f_s as well as the obscuration size limit. Results from a study done by Menapace[15] show that contaminants typically found on large-scale laser-glass amplifier glass create laser glass damage 7.7x as large as the original contaminant size (Fig. 1) when exposed to 10-J/cm^2 flashlamp light.

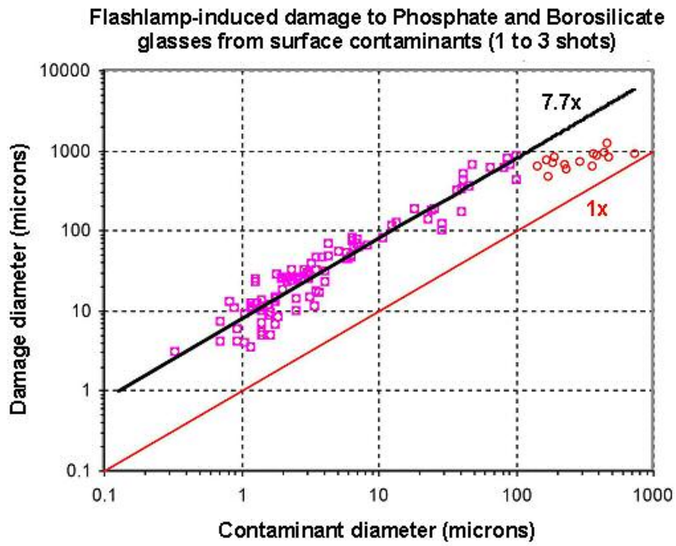


Figure 1. Plot showing the damage size vs. contaminant size for flashlamp-induced laser-glass damage [15].

2.1 Fed Std 209

Airborne, or volumetric cleanliness *Class*, is defined by Fed Std 209 and is given by

$$f_{vol}(x) = Class \times \left(\frac{0.5}{x}\right)^{2.2} \tag{2}$$

where $f_{vol}(x)$ = particles/ft^3 $\geq$ diameter and

x = particle diameter in µm.

This equation is often plotted (Fig. 2) as a series of straight lines on log-log axes where there are upper limits on particle sizes depending upon the *Class*. The mathematical form of, and slope or exponent = 2.2 found in this equation are derived from measurements made in various types of laboratory cleanrooms. Volumetric cleanliness outside of a cleanroom environment may have significantly different slopes and even varying slopes over the distribution depending upon the environment[16,17,18]. A very clean volume with little flow and no activity will have a slope >2.2 while a room with significant activity will have a slope <2.2. The shape of the volumetric distribution makes intuitive sense as large, heavy particles are less affected by buoyancy and fall out first. The volume of each of the 11-slab long main amplifiers is ~12m^3 ~ 420ft^3. If one were to take this distribution for *Class 1000* out to infinity, eq. (2) would predict three 100-µm sized particles in the amplifier. In reality, the distributions of Fed Std 209 are only defined over a certain range and the high-end the particle range decreases as the *Class* decreases[11]. It would be extremely rare to find any >100-µm particles in a cleanroom aerosol environment without human activity or some other anomalous event.

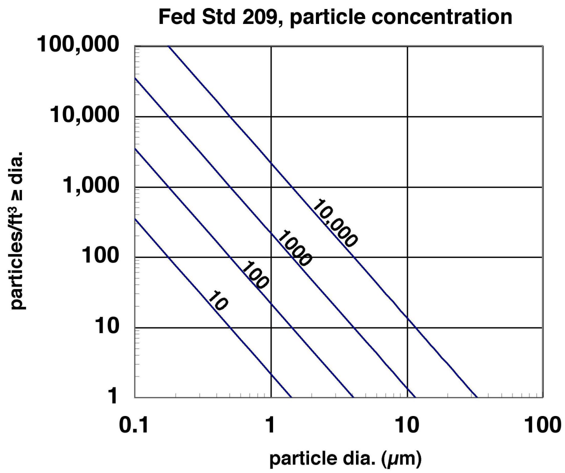


Figure 2. The cumulative distribution of airborne particles found in typical cleanroom environments as given by the Fed Std 209.

2.2 Mil Std 1246

The Mil Std 1246 defines a surface cleanliness *Level* for particles larger than 1 μm that is defined by

$$\begin{aligned} f(x) &= 10^{0.926x\left[\log_{10}^2(Level)-\log_{10}^2(x)\right]} \\ &= e^{C\left[\ln^2(Level)-\ln^2(x)\right]} \end{aligned} \tag{3}$$

where $f(x)$ = particles/ft^2 ≥ diameter,

x = particle diameter in μm, and

C = 0.926/ln(10).

This equation is often plotted as a series of straight lines on log-log^2 axes. On log-log axes, the data take on the shape of a curve as shown in Fig. 3.

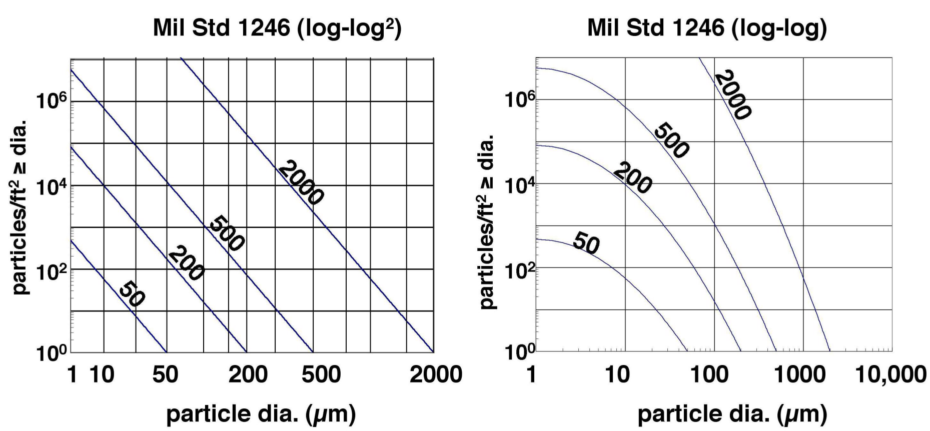


Figure 3. The distribution of particles on just-cleaned surfaces as given by the Mil Std 1246 plotted on log-log^2 axes (straight lines) as well as log-log axes. The surface cleanliness, or *Level*, for each curve is shown.

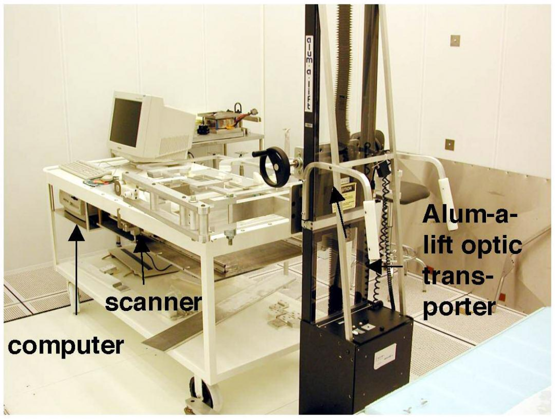
The mathematical form of, and constant value (0.926) found in this equation are derived from measurements on just-cleaned surfaces. The relatively steep slope (0.926) of the curve makes intuitive sense as large particles are the most easily removed when cleaning a surface. When surfaces are exposed to an environment, the surfaces accumulate particles due to fallout and the distribution tends to flatten out, i.e., the particle distribution is similar to Mil Std 1246 but with a constant, or slope less than 0.926. Data from a number of large-scale clean facilities have shown that the slope of the surface contamination distribution due to fallout ranges from as low as 0.3 to 0.8[16,19,20]. It is important to point out here that the Mil Std 1246 distribution cannot be obtained from the Fed Std 209 distribution. Particles in an aerosol settle out at the Stokes velocity[21], $v_s(x) = K_s x^2$, where x is the particle diameter and K_s is a constant. Integrating $df(x)/dx*v_s(x)$ to obtain $g(x)$, the net cumulative surface distribution per unit time of settled aerosol particles results in

$$\begin{aligned} g(x) &= \int_x^{\infty} \frac{df(x)}{dx} v_s(x)\, dx \\ &= 11 K_s\, Class\,(0.5)^{2.2} x^{-0.2} \end{aligned} \qquad (4)$$

This distribution is far flatter than the Mil Std 1246 and would over-predict the number of large particles. Others[16,19] have derived empirical relationships between aerosol and resultant surface contamination but these relations work best for large volumes, over large periods of time, and with significant human activity. In general, predicting surface distributions from aerosol fallout distributions is difficult and can only be done in well-controlled, simple environments[17,18]. While aerosol cleanliness and surface cleanliness measurements give a relative sense of system cleanliness, ultimate amplifier cleanliness and relative performance is based on the laser glass obscuration measurements.

2.3 Flatbed scanner

During the decommissioning of Nova, a slab scanning technique was developed using a large-format flatbed scanner. Photographs of the flatbed scanning system are shown in Fig. 4. The system consists of a commercial,



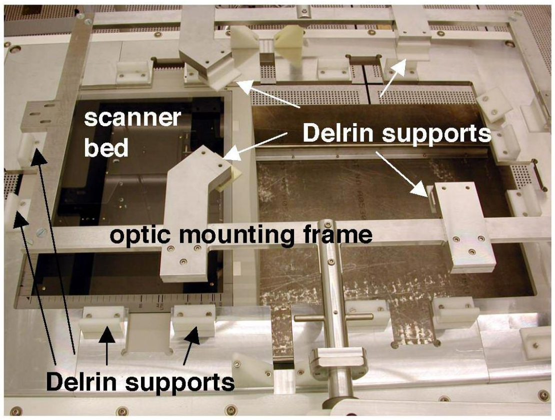


Figure 4. Two separate views of the flatbed scanning system for large optical components. The photograph at left shows the cart that contains the computer, flatbed scanner, mounting hardware, and Alum-a-lift optic transporter. The photograph at right is a top view showing the flatbed scanner bed and various Delrin supports that can be adjusted to hold different sized optics.

large-format flatbed scanner with custom-built support hardware and software. The system is cleanroom compatible and can safely deliver and load the large optics (up to 45cm x 75cm) onto the scanner bed. The flatbed scanner has a large depth-of-field and images both sides of a 4-cm thick piece of glass. The opacity of the laser-glass slabs is such that only the surface nearest the scanner is imaged. An 800-dpi (31.5μm/pixel) flatbed scanner system was built in 1999 and a 1600-dpi (15.75μm/pixel) flatbed scanner was built in 2002. Depending upon the size of the laser glass, up to three separate scans might be stitched together to form an image of a single, laser-glass surface. Despite only an 8-bit pixel depth, the digital storage requirement for a single image can be as large as 512Mb. Software was written to handle these large files as well as identify, size, and count the obscurations.

3. Historical Results

Cleanliness measurements and obscuration results from four recent large-scale laser systems will be presented and compared. These large-scale laser systems are Nova, Beamlet[22], LIL[23], and NIF.

Nova had 10-beams in a single-pass architecture and operated at 1ω fluences near 10 J/cm^2. Just prior to, and during, its de-commissioning in 1998, a number of cleanliness measurements were made. It was during the analysis[7] of these cleanliness and obscuration measurements that we observed that Nova laser-glass damage was not correlated with the number of laser shots (for 180 < shots < 8000). Beamlet was the prototype for NIF and used large, 40-cm optics. Beamlet was de-commissioned in 1999 after ~1500 shots. Beamlet laser glass-damage was also un-correlated with number of shots. The Beamlet laser is currently installed at Sandia National Laboratories. The LIL (Ligne d'Integration Laser) is the prototype for the LMJ (Laser MegaJoule)[23,24]. Prior to actual laser experiments on LIL, a number of cleanliness-related experiments were performed and measurements were taken. The final set of these cleanliness experiments was named Phase C0 and was taken over 33 flashlamp shots in August 2001. No laser beam was present. For comparison, NIF performed a similar cleanliness experiment consisting of 40 flashlamp shots (no laser beam present) in July 2002.

3.1 Aerosol measurements and comparisons

While we have never determined a precise, quantitative link between aerosol concentration and resultant flashlamp-induced laser-glass damage, offline and actual experiments have given us a qualitative understanding of this link. Experiments where no aerosols are generated result in no flashlamp-induced damage to the laser glass[10]. Experiments where aerosol concentrations remain high (>10^5 particles/ft^3 0.5 μm and larger) or increase for long periods of time tend to indicate burning of organics and/or NVR (non-volatile residue) transport and result in significant laser-glass damage[25,26,27,28]. These small organic particles often agglomerate during or after transport to form relatively large (>10 μm) particles or droplets, which may then deposit on the laser glass, absorb flashlamp light, heat up, and damage the laser glass[15]. Amplifier cavities that are purged at sufficiently high rates may sometimes sweep out these undesirable particles before they settle on the laser-glass surfaces[15,27]. If an aerosol-free environment cannot be achieved, a rapidly decaying low-aerosol concentration with few large particles is the next-most desirable. Aerosol measurements made in the four large-amplifier systems described above are shown in Fig. 5.

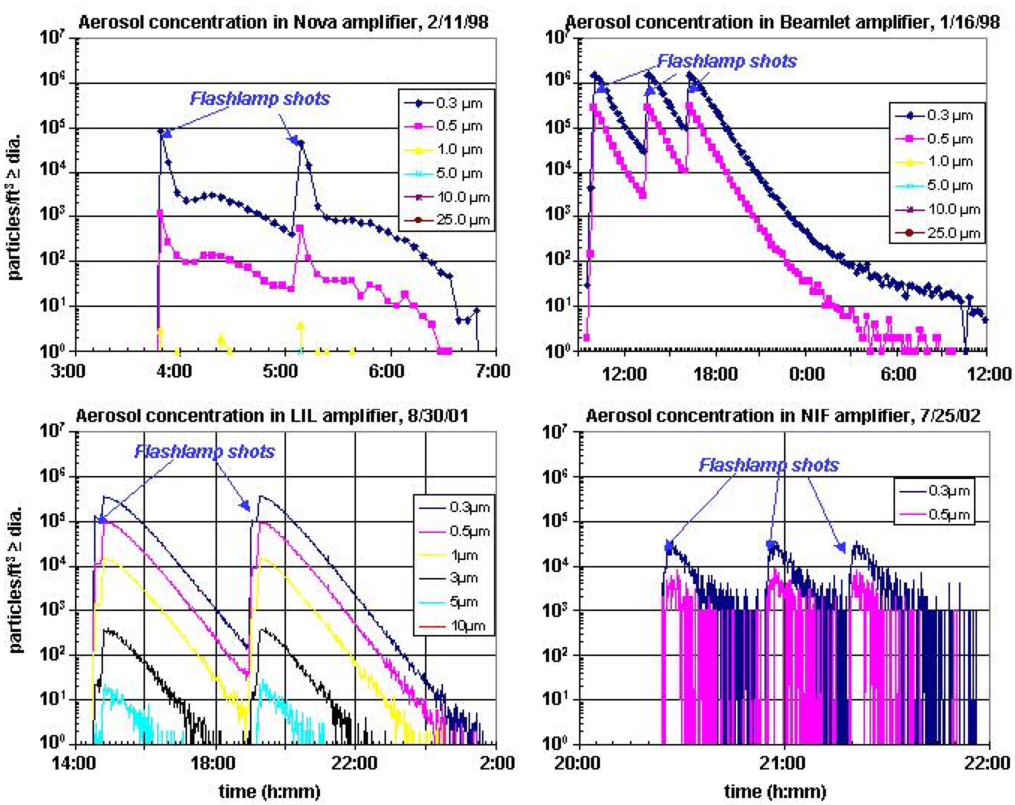


Figure 5. Typical aerosol concentrations of large-scale laser amplifiers immediately after a flashlamp shot.

In each of the four cases in Fig. 5, there is a sudden rise in aerosol concentration immediately after a flashlamp shot followed by a decay that corresponds primarily to the purge rate and duration but also to the cleanliness of the system. Nova, Beamlet, and LIL amplifiers were all purged with nitrogen gas at 5, 1.5, and 10 exchanges/h, respectively. The NIF amplifiers are purged with ULPA-filtered CDA (clean dry air) at 6.5 exchanges/h. The Beamlet and LIL amplifiers used 6-channel aerosol counters that allow us to look at the change in aerosol distribution as a function of time. These plots are shown in Fig. 6. Although the peak aerosol concentrations are nominally the same, the distributions are different from each other and different from the Fed Std 209 distribution. The amplifier aerosols have a much steeper distribution (fewer large particles) than the Fed Std 209 would predict. The LIL aerosol distributions are steep, indicating very few large particles. Despite a slower purge rate, the Beamlet aerosol distribution decays ~50% quicker. [Each curve represents the aerosol distribution for a 1-mn interval.] The optimum scenario would be a rapidly decaying, steep aerosol distribution.

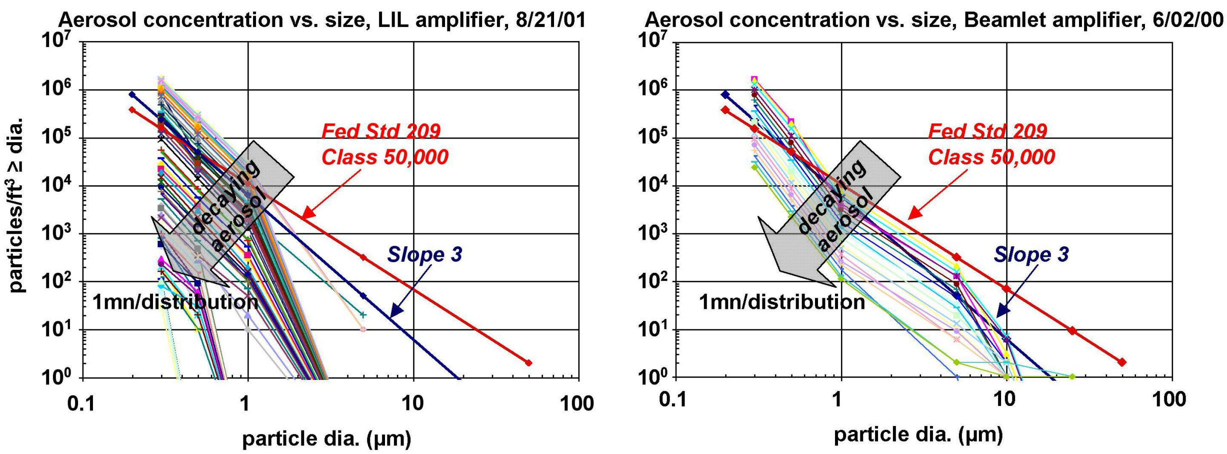


Figure 6. Plots showing the decay of the aerosol distributions in the LIL and Beamlet amplifiers.

The Nova amplifiers had relatively low peak aerosol concentrations but these measurements were made after years of operation. Based on our observation that Nova laser glass damage was independent of the number of shots[7] (180 < number of shots < 8000) and offline experimental results[10] we believe that the laser amplifiers can undergo a process of flashlamp cleaning. Barring any large, semi-infinite contamination source, a number of flashlamp firings followed by amplifier purges improves the cleanliness of the amplifier and reduces the peak aerosol concentrations. This flashlamp cleaning process was observed during the commissioning of the first NIF amplifier. The amplifier section of NIF is grouped into bundles of 8 beams, 2 beams wide by 4 beams high[29]. The main amplifier section for each NIF bundle consists of 88 slabs and is pumped by 5.5 modules of flashlamps, where each module consist of 40 flashlamps that pump a 2 slab-length of amplifier[29,30]. Figure 7a shows the aerosol concentrations in the empty main amplifier bundle (no laser glass installed) after the very first flashlamp shots. The first flashlamp shot was a single module at a voltage of 18kV. The second flashlamp shot was identical to the first and note the drop in aerosol concentration. The third and fourth shots were at higher flashlamp voltages and the aerosol concentrations remained steady and even decreased. After ~20 more flashlamp shots, the aerosol concentrations shown in Fig. 7b had decrease ~250x, with full-bundle (5.5 modules) flashlamp shots at 23.8kV. The amplifier volume was purged with ULPA-filtered CDA after each flashlamp shot at a 6.5-exchange/h rate in order to sweep out as many particles as possible. While decreased aerosols are always desirable, the best metrics of amplifier cleanliness are flashlamp-induced slab obscurations.

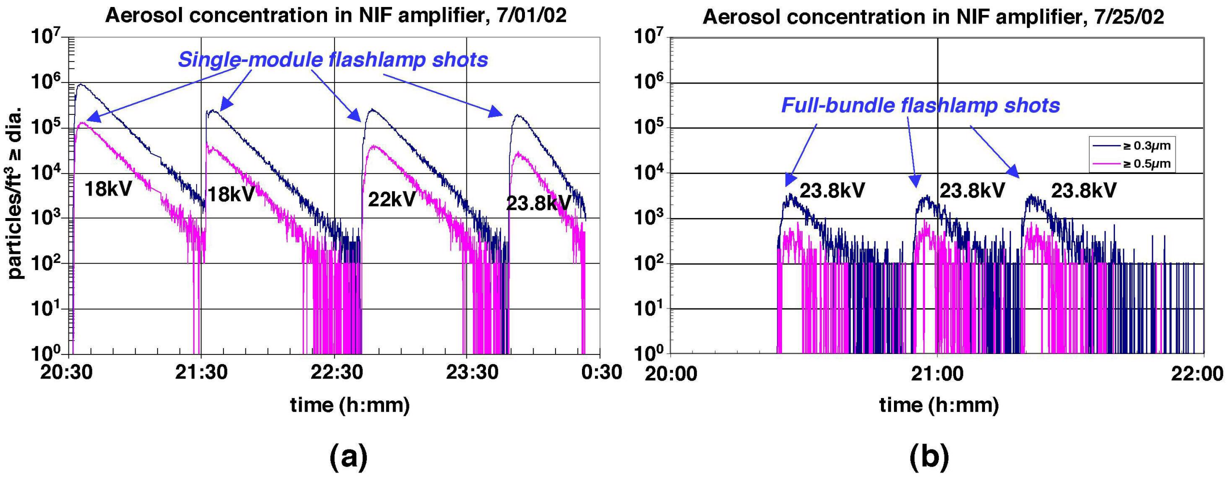


Figure 7. Plots comparing the NIF amplifier aerosol concentrations during the first flashlamp shots and later flashlamp shots.

3.2 Slab obscuration measurements and comparisons

As discussed in Sec. *2.2*, the Mil Std 1246 distribution is valid only for just-cleaned surfaces. From typical fallout data as measured here and by others, we see that fallout obeys a pseudo-Mil Std 1246 distribution that we define using a pseudo-level, or *pLevel* in the distribution

$$f_d(x) = e^{C\ln^2(pLevel)}\ e^{-C_s \ln^2(x)} \tag{5}$$

where $f_d(x)$ = damage obsucrations/ft^2 ≥ diameter,
x = obscuration diameter in μm,
C = 0.926/ln(10) , and
C_s = *slope*/ln(10) .

From our work to date, we have found that the obscurations on the laser glass for all four of the large-scale lasers discussed in this paper have a distribution given by eq. 5 with *slope* = 0.5. Surface cleanliness distributions due to aerosol fallout typically have slopes that range between 0.3 and 0.8[16,19,20]. The laser-glass obscuration data from four large-scale laser amplifiers are shown in Fig. 8. During the de-commissioning of Nova, we found that this obscuration distribution of eq. 5 held true whether the laser disks were scanned before or after cleaning. The cleaning step might remove anywhere from 30% to 90% of the obscurations but the shape of the distribution was essentially unchanged[7]. The majority of the removable/clean-able Nova contaminants were found to be silica from the deterioration of the flashlamp blastshield windows. While there is a relatively large spread in the Nova data, the shapes of the four distributions are remarkably similar. The Nova laser disks had between 180 and 8000 flashlamp shots. Beamlet laser-glass slabs had a similar spread in data but significantly fewer obscurations. The Beamlet slabs had between 300 and 1500 flashlamp shots. The LIL Phase C0 cleanliness experiment consisted of 33 flashlamp shots (no propagating laser). The flatbed scanner was loaned to LIL and the obscuration data from the Phase C0 experiment are shown in Fig. 8. Four laser-glass slabs (8 surfaces) were scanned prior to and after the experiment. The NIF experiment[31] consisted of 40 flashlamp shots (no propagating laser). As with the LIL Phase C0 experiment, 4 laser-glass slabs (8 surfaces) were scanned prior to and after the experiment. Each successive generation of large-scale laser shows fewer obscurations than the previous.

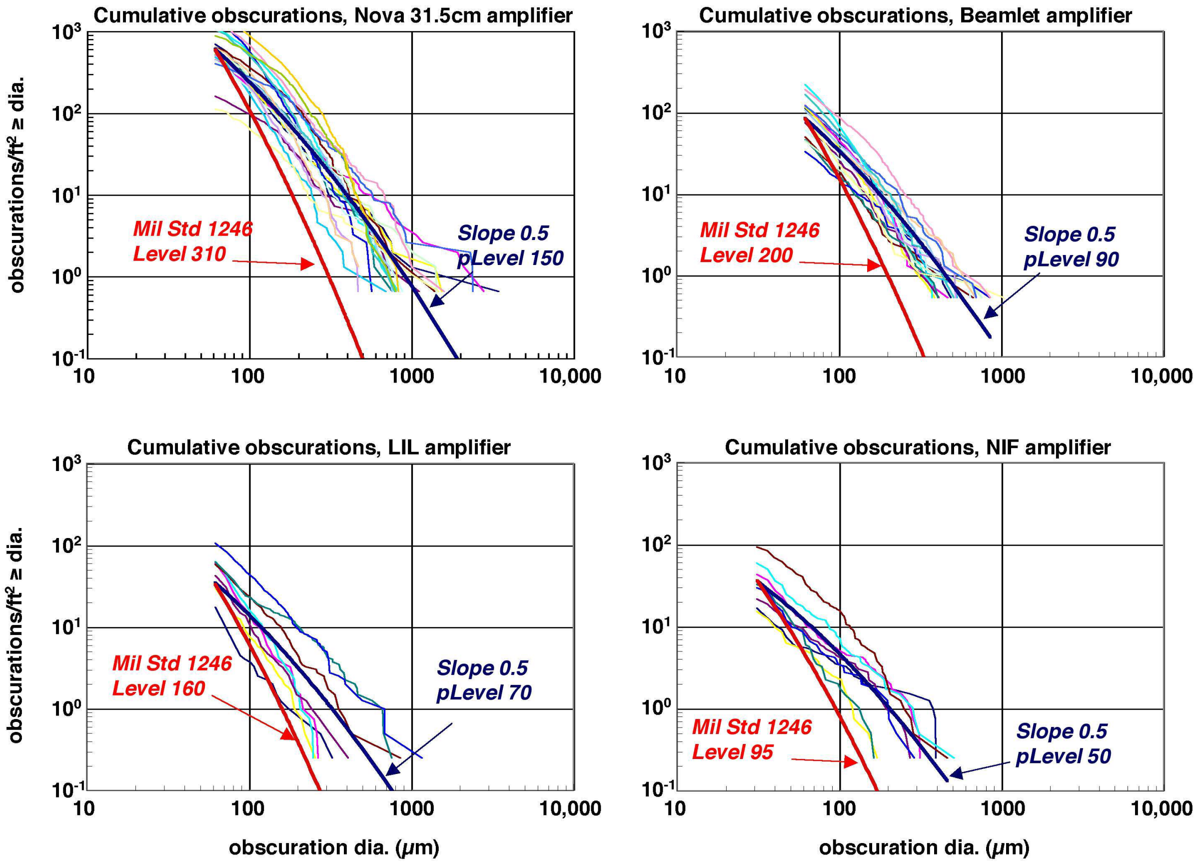


Figure 8. Laser-glass obscuration data from four large-scale laser amplifiers.

4. Discussion

Determining how clean is "clean enough" for a laser amplifier is difficult since there is no direct link between easily observable cleanliness metrics (e.g. aerosols and surface cleanliness of nearby hardware) and resultant damage[7,27]. In offline experiments using very clean, small laser glass coupons and elastomer-free stainless steel chambers, we have observed the null case of no surface contamination, no aerosol, no damage[10]. Building a NIF-class laser in such a fashion would prove to be nearly impossible and prohibitively expensive. At the extreme temperatures generated by the flashlamps, aerosols will be created wherever there are exposed particles, elastomers, or organic films. The NIF has gone to great lengths to clean as well as possible to minimize exposed particles and prevent the creation of particles[2]. In addition, NIF uses relatively few elastomers and these have either been tested to withstand flashlamp light or are shielded. Finally, NIF has a fairly tight NVR (non-volatile residue) organic film requirement (<A/10) for the amplifier[32]. Offline experiments have shown that when NVRs are exposed to flashlamp light, they can transport as either a film or as globules, depending upon the NVR constituent and upon the hardware or optic surfaces[27,28]. These small globules can then burn, turn black and cause substantial damage to optics[15].

The obscuration data tend to follow the *pLevel* formalism of eq. 5. If we assume that the obscurations are circles, we can integrate eq. 5 to obtain a scattering fraction, η, or

$$\eta = \int_1^\infty -\frac{\partial}{\partial x} f_d(x) \pi \frac{x^2}{4} dx / (beam\ area)$$

$$\eta = \frac{1}{4}\pi e^{C\ln^2(pLevel)}\left[e^{\frac{1}{C_s}} \sqrt{\frac{\pi}{C_s}} \left(1 + erf\,\frac{1}{\sqrt{C_s}}\right) + 1\right] / (beam\ area) \tag{6}$$

The average Beamlet obscuration fraction per surface (using *slope* = 0.5, *pLevel* = 90) is $\eta_{Beamlet} = 2.2\text{x}10^{-5}$. There is a wide spread in the data but these results are quite encouraging since even the worst NIF data are better than the average Beamlet data and well below the $2.5\text{x}10^{-4}$ obscuration/surface specification for NIF. Nova and Beamlet had far more shots than LIL and NIF, but our experience[10] and data analysis of Nova[7] and Beamlet indicate that laser glass obscurations are not correlated with the number of flashlamp shots when the number of shots exceeds 180. Assuming no anomalous or catastrophic amplifier event, we believe that the vast majority of laser-glass obscurations occur within the first ~10 shots. In the worst case, linearly scaling our 40-shot results to 180 shots would leave NIF well below its $2.5\text{x}10^{-4}$ obscurations/surface specification. A series of in-situ visual inspections[33] of the LIL amplifier laser glass and hardware during the Phase C0 experiments showed some small chips and burns on hardware and laser glass but far less than were observed on Nova and Beamlet. Post-experiment visual inspections[34] of the NIF amplifier laser glass and hardware showed only two burn marks (hardware) and <1 actual damage site per laser-glass surface. Much of this marked improvement in visible burn marks and laser-glass damage is in all likelihood due to cleanliness practices, material selections, minimization and improved shielding of organics, as well as flashlamp cleaning of the empty amplifier cavity prior to laser glass insertion. A >100x reduction in laser amplifier aerosol concentration was observed between the first NIF flashlamp shots and the shots during the cleanliness experiment

Since the obscuration data for the four large-scale amplifiers described in this paper have the same *slope*, we can reasonably represent the spread in data for each amplifier using the 100-μm point of the obscuration distribution. Data comparing the obscurations for these four large-scale amplifiers are shown in Fig. 9. We see from these data that amplifier cleanliness, as measured by slab obscurations, has improved from generation to generation.

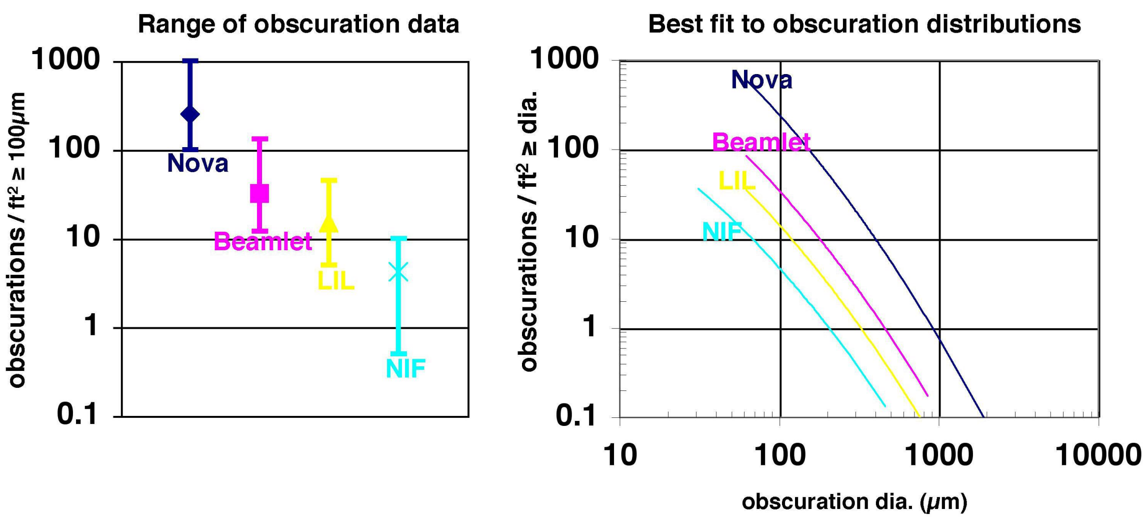


Figure 9. Plots comparing the obscuration data of laser glass from successive generations of large-scale laser amplifiers.

5. Summary

Aerosol measurement and obscuration data obtained from NIF and previous large-scale laser amplifiers have been reduced and compared. The laser-glass obscuration data were obtained using a modified flatbed scanner system with custom software. We have found that the aerosol distributions are steeper than the Fed Std 209 distribution and contain very few large particles. Since the aerosol data were not obtained at the same point in each amplifiers lifetime, the data cannot be fairly correlated with resultant laser-glass obscurations. However, firing the flashlamps prior to laser glass insertion reduces peak aerosol concentrations, especially during the first few shots in an amplifier lifetime. Obscuration data are more representative of amplifier cleanliness. We have found that the laser glass obscuration distributions have a pseudo Mil Std 1246 distribution with *slope* = 0.5. While traditional cleanliness measurements give us a sense of overall cleanliness and ultimately, laser performance, laser-glass obscurations are a more definitive measure. We have presented cleanliness results, both traditional and flatbed scanner, for these 4 lasers and have shown a progressive improvement in cleanliness, with NIF being the cleanest large-scale laser ever built.

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Figures and Photos

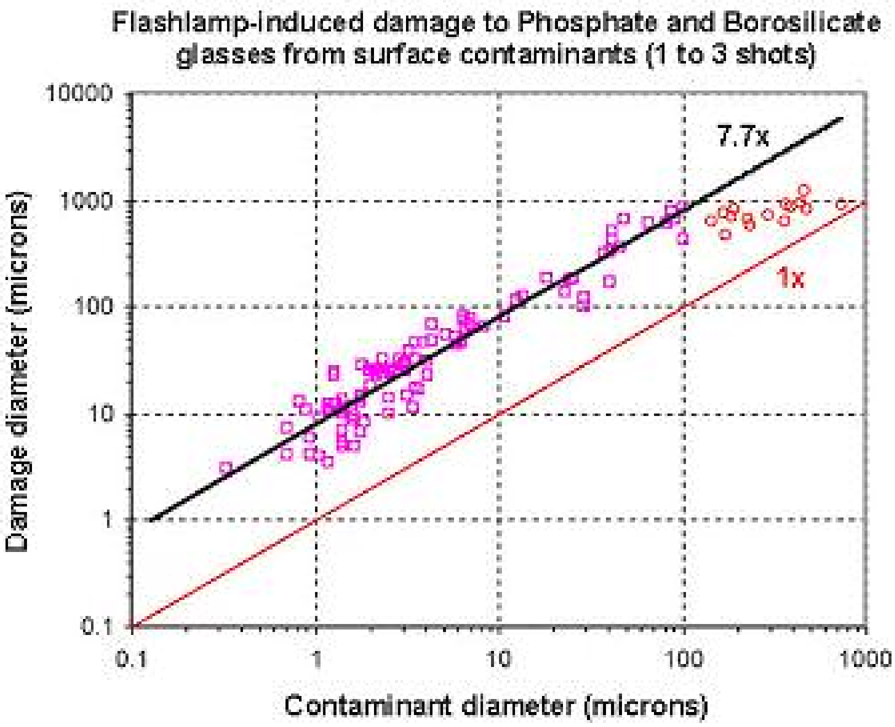


Figure 1

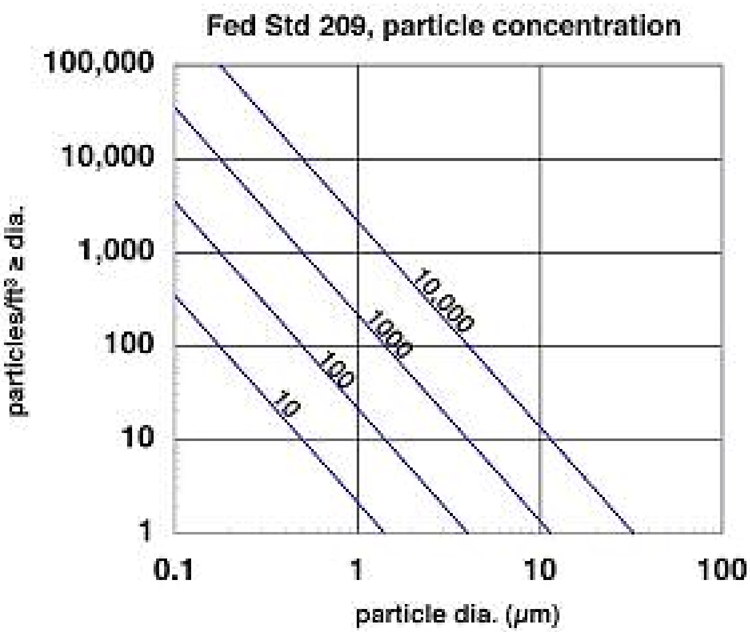


Figure 2

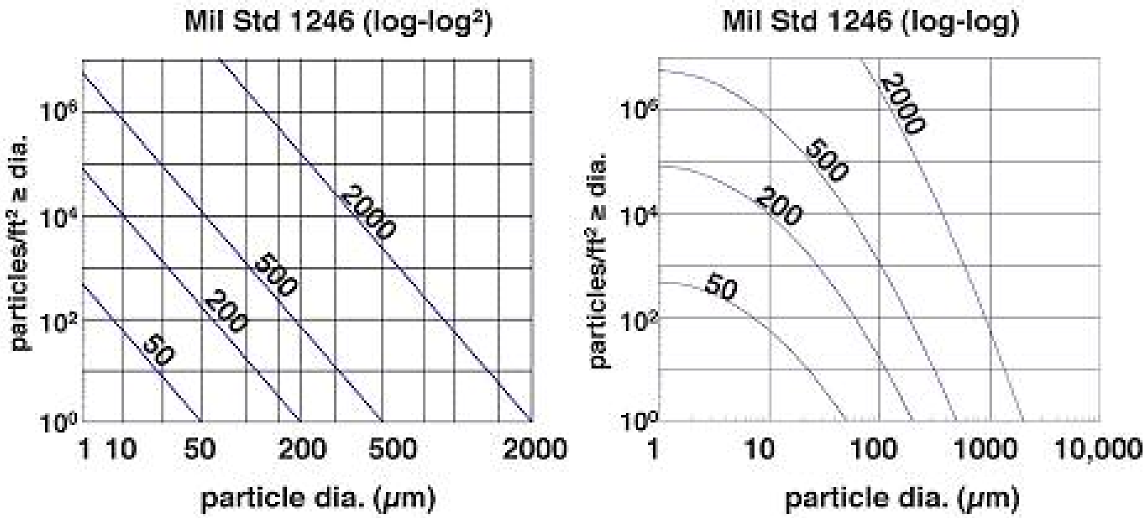
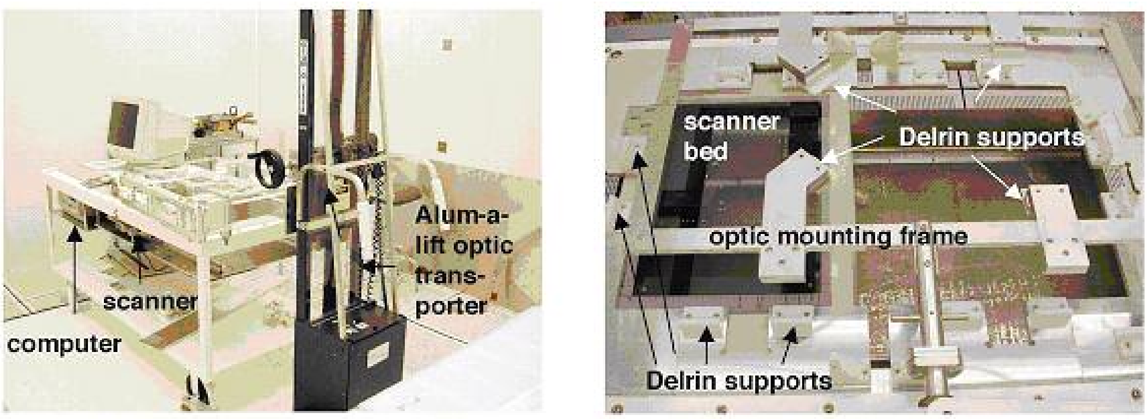


Figure 3



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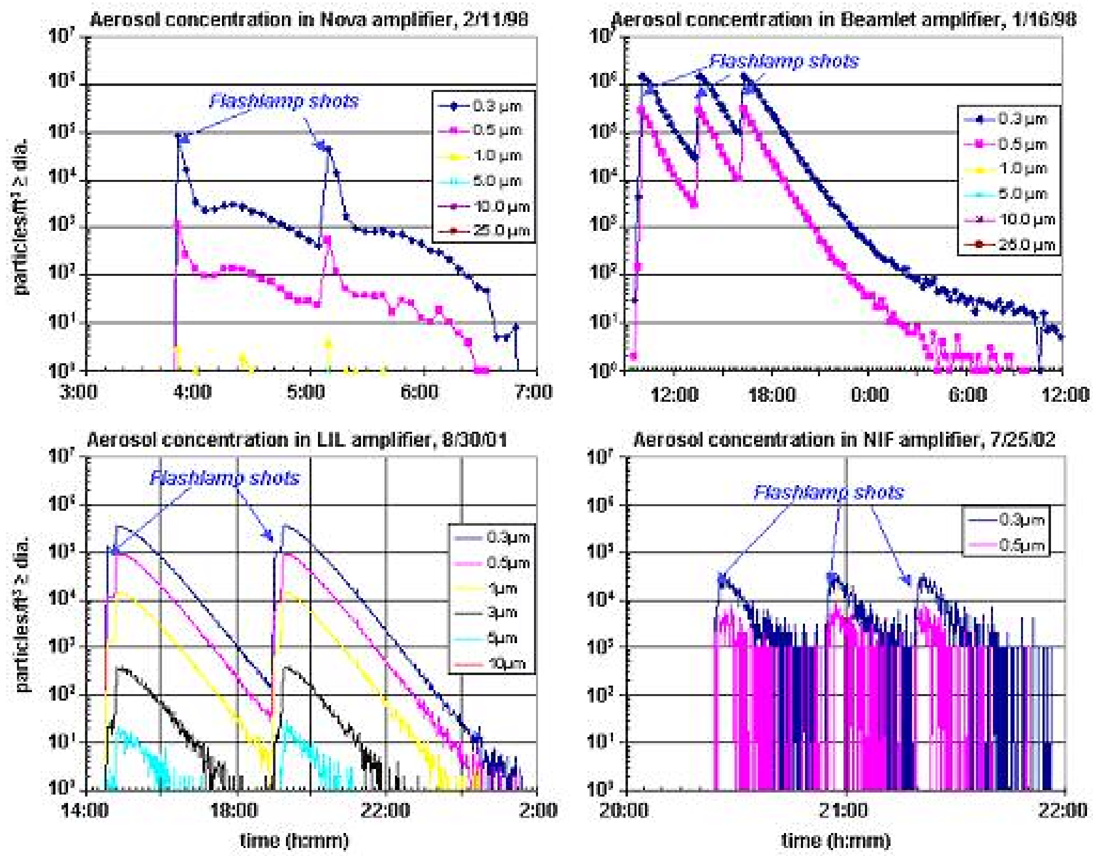

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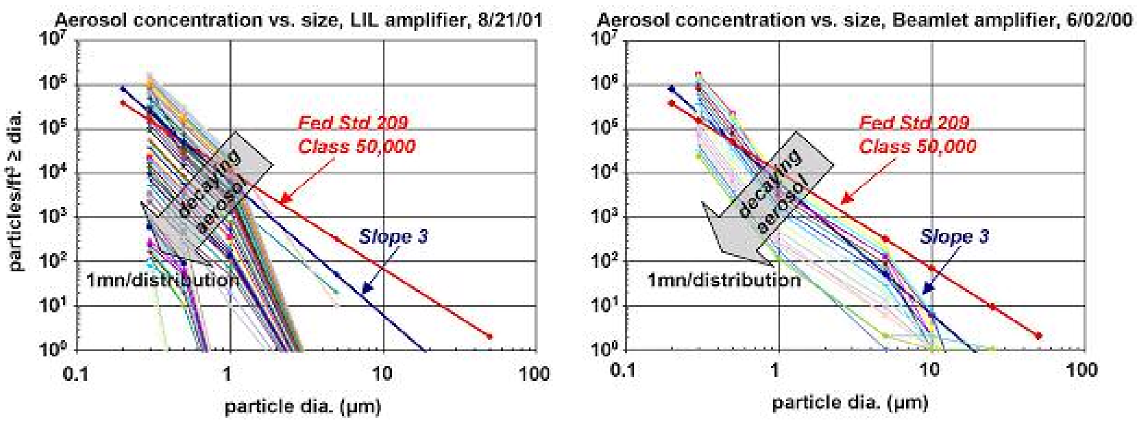

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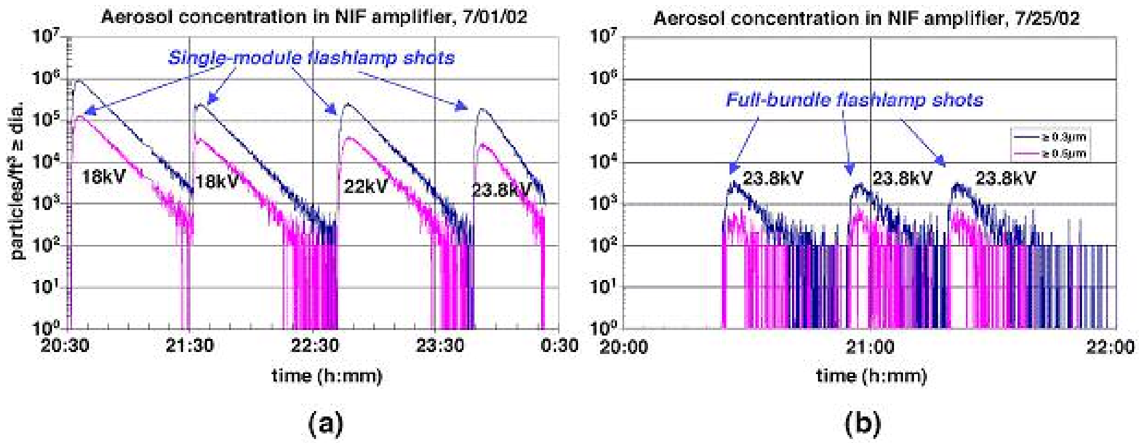

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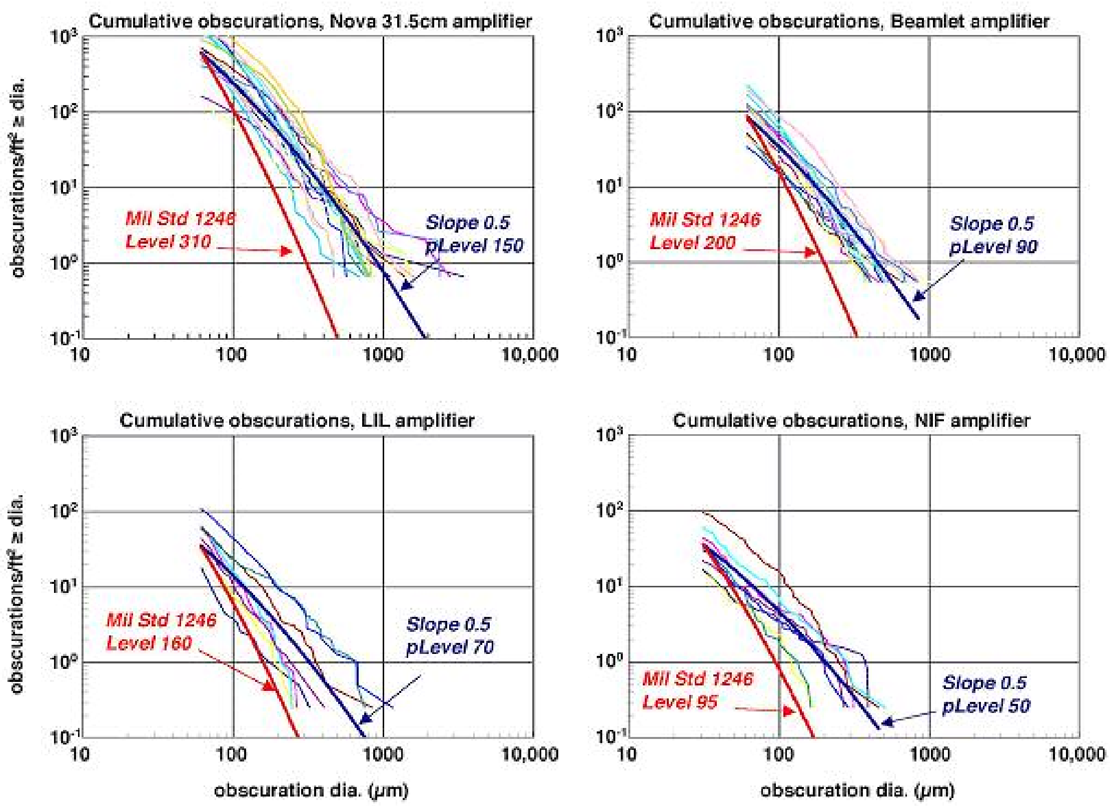

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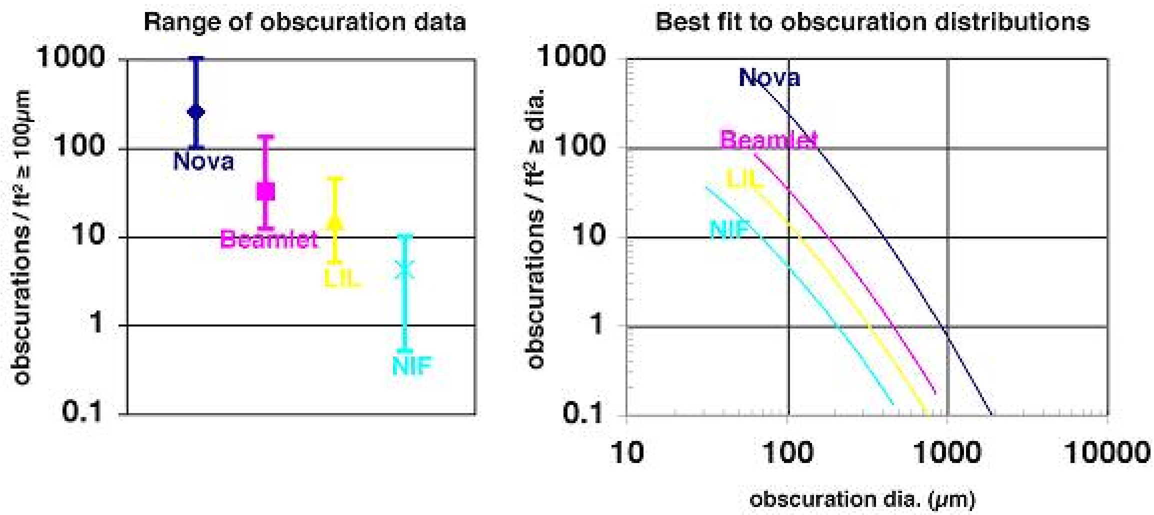

Figure 9

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